AN AUTONOMOUS OPTICAL NAVIGATION AND CONTROL SYSTEM FOR INTERPLANETARY EXPLORATION MISSIONS

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ABSTRACT:
The first fully autonomous deep-space navigation system ever implemented is planned to guide the *New Millennium Deep Space-1* mission to an asteroid and comet beginning in mid-1998. This system is based to a large extent on Optical Navigation (OPNAV) technology developed for the NASA/JPL interplanetary exploration probes *Voyager* and *Galileo*. This paper describes the structure and algorithmic content of the Autonomous OPNAV system. The System has several major autonomous functions: picture planning, image analysis, orbit determination, maneuver design and general interaction with other onboard autonomous systems. New algorithms and processes have been developed to navigate in deep-space with optical only data, and to process the resultant images taken from a small spacecraft. Since *DS-1* will use Solar Electric Propulsion (SEP) new trajectory control algorithms were developed. The prototype system has been tried on several mission scenarios.

INTRODUCTION:
Autonomous onboard optical navigation will be a necessary component of autonomous spacecraft operations for many future planetary exploration missions. Bemuse of light travel times, there are experiments and even missions that cannot be performed or have limited data potential unless autonomous navigation systems are incorporated. Close orbits around, or very fast flybys of, small poorly characterized objects are examples of such missions. Reducing operational complexity and costs is another goal of autonomous navigation systems. In a not-too-distant future, many small robotic missions may be simultaneously exploring the solar system. To increase the efficiency of these missions, the spacecraft themselves must take on more of the responsibilities of their own maintenance, including navigation. Adapting many of the techniques proven for optical navigation for *Voyager* and *Galileo*, the New Millennium onboard navigation system must autonomously plan picture sequences, perform image analysis, estimate the trajectory and calculate trajectory corrections using the low-thrust Solar Electric Propulsion system. New *Millennium DS-1 will* be the first planetary exploration mission to autonomously navigate all mission phases. The engineering of such a navigation, system poses a number of very significant challenges.

The presence of an autonomous navigation system onboard a spacecraft imposes certain requirements on the onboard 'autonomous control" system, and in turn, the capabilities and function of the control system will influence the architecture of the 'Navigator" In fact, one of the more important developments of the navigation system is the construction of this interface. The nature of the interaction is to balance the resource needs of the navigation system with those of equally important onboard engineering and mission science objectives. These resources include use of the camera, slew time, mass storage capacity, fuel use, use of the system computer and total time in the sequence of events. The amount of resources devoted to the Navigator will often translate directly into performance of the system.

HISTORY OF OPTICAL NAVIGATION IN DEEP SPACE:
The *Voyager 1* encounter with Jupiter in March 1979 was the first planetary mission which required optical navigation for mission success[1]. The science sequences were designed assuming the spacecraft position would be controlled to the capability of the optical navigation system, a few tens of kilometers, *vs.* the radio system capability of many hundreds of kilometers. One critical advantage of optical navigation at encounter is the target relative nature of the measurements. A substantial source of a *priori* uncertainty in the encounter geometry is the target ephemeris uncertainty. For many targets this uncertainty cannot be adequately addressed in any other way than local observation provided by imaging. However, even for the gas giant planets themselves, the *Voyager* encounters made substantial snd very important improvements in the planetary as well as satellite ephemerides.

The technique used in the *Voyager* optical navigation system was a prototype for all such systems. Images of the Galilean satellites were taken against the background field of stars. The difference between observed and expeced images provided information on the relative cross-line-of-sight positions of the spacecraft and satellites. The principal difficulty the OPNAV system experienced was the limited dynamic range of the Vidicon cameras. This limited range resulted in the overexposure (often severe) of the images, reducing the accuracy of the data. For these two encounters the net accuracy of the OPNAV data was on the order of .75 pixels, or ?.5 micro radians. This high-accuracy measurement represented an error of only 5km at three days from closest approach.

For the *Voyager* Uranus and Neptune Encounters, improved technology .-. redesigned models and procedures, and most importantly, a reduced dynamic range problem because of reduced solar flux in the outer solar system ---

provided substantial improvement in the quality of the OPNAV analysis[2,3]. For these encounters the net system error was reduced to .15 and .10 pixels respectively, and the most demanding science sequences of the Voyager mission were achieved taking advantage of the improved OPNAV performance. So good had detection analysis and subsequent orbit analysis become by Neptune (the *Voyager* mission, and the OPNAV team in particular, had by that time been responsible for discovering about two dozen new satellites around the Gas-Giants) that Neptune navigation strategy assumed the early discovery of a new satellite, and its subsequent critical use in navigation for the encounter. The satellite in fact was discovered "on time" at about 30 days from Neptune, and became an invaluable beacon object for the encounter operations, as well as an important science target.

Of course, none of the OPNAV process for *Voyager* was autonomous. All image analysis was performed on the ground, and the reduced optical data was combined with the very high quality radio metric data. No attempt had been made to plan an optical data arc that could navigate, the encounters "optical-only. " Maneuver analysis was performed on the ground, with parameters integrated into ground-generated comnrand sequences. Even though for the most critical trajectory correction maneuvers (TCM's) this process could be accomplished in as little as 6 hours from the receipt of the last data to uplink of the TCM command, it was still a highly interactive and labor intensive procedure.

The ***Galileo Mission*** inherited basically the same OPNAV system as ***Voyager. Galileo even*** inherited some of the dynamic range problem. Though the camera was equipped with a CCD sensor, it was a very early device linked to an 8-bit analog/digital encoder. The dynamic range limitations are somewhat ameliorated by the set-able gain of the instrument, and the high-solar-phase of most of the Galilean tour pictures. Unfortunately, the loss of *Galileo's* high gain antenna necessitated some dramatic changes in OPNAV processing. The most fundamental problem posed by the loss was a drastic reduction in the down link data rate. On approach to the first planned asteroid encounter with Gaspra, instead of the planned dozens of approach OPNAV frames, the schedule would allow for a maximum of five, With normal processing such a schedule would have been inadequate to capture the high resolution images that were desired. A technique was devised by the OPNAV team to pack the equivalent of up to a dozen images into a single exposure. Called a Single Frame Mosaic (SFM)[4], this technique will be used extensively in the autonomous OPNAV system being developed for *New* Millennium *DS 1*. For the Galilean satellite tour the same restrictions on telemetry apply. For this reason a very basic automated OPNAV image processing capability has been developed to fly onboard the Galileo spacecraft, This system makes use of the predicted limb pattern of a satellite, and the roughly predictable satellite to star vector (usually predictable to within a few pixels) 'the algorithm searches a newly shuttered frame for a pattern nearly like the uplinked pattern. Once the pattern ia recognized the position of the located limbs is noted (the position of the satellite may be Up to 200 pixels away from the predict) and the stars can then be located. Data from both the satellite and star is then down linked with a net savings of over 99 percent of the down link relative to transmitting the entire image. This algorithm has also found uae in the ***DS-1*** OPNAV system.

MISSION ATTRIBUTES AND REQUIREMENTS:

The *DS-1* mission plan is still under development at this writing, but it will almost certainly be the caae that the mission design will include a flyby of an asteroid followed by a flyby of a comet[5]. A further driving mission characteristic is that the principal means of propulsion for the spacecraft will be Solar Electric Propulsion (SEP); and the SEP system dominates the physical design of the spacecraft (Fig. 1). This type of "low thrust" propulsion enables many mission opportunities for low-mass spacecraft due to the very high efficiency of ion propulsion vs. chemical (hydrazine) propulsion. At the same time however, the navigation problem becomes considerably more complex, and for a deep space mission, unprecedented. The principal differences for navigation between the two propulsion systems are: 1) The mission design process must make uae of tools specifically tailored for dealing with SEP powered spacecraft. 2) Controlling the spacecraft trajectory ia performed by means of periodic or continual updatea to a planned thrust profile instead of widely spaced discrete maneuvers. 3) The dynamic noise introduced into the trajectory by the SEP engine, though small, ia much larger than any previous "non-gravitational" perturbations experienced during the cruise portion of a deep space mission. The latter consideration has an important influence on the design of the estimation filter (see below).

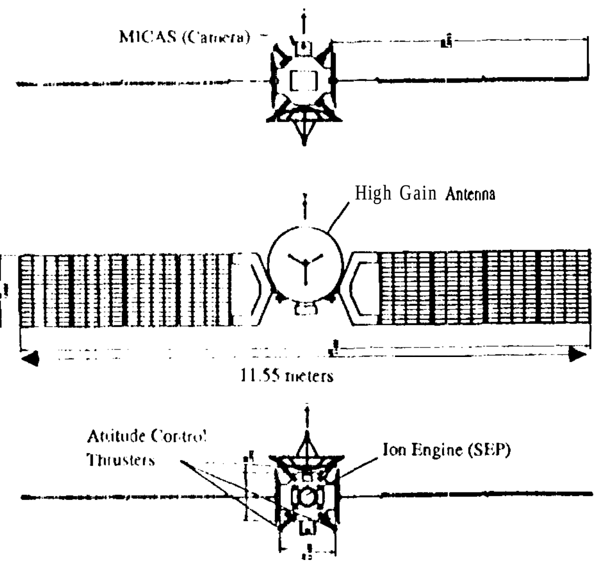

Fig 1: *New Millennium DS1 Spacecraft*

The primary emphasis of the New ***Millennium*** Program is technology validation. The intent is to demonstrate technologies that will prove necessary or enabling for future missions. As such, there are no overriding science requirements. But in a useful correlation of objectives, the nature of the validation of the navigation system is one which would provide for the greatest science return. In general, this will require the navigation system to achieve high accuracy control, both of the spacecraft trajectory and of camera (spacecraft body) orientation during the encounter periods. Requirements on trajectory control during the cruise are much looser, and the effective requirement is to control the trajectory to as accurate a level as necessary to achieve the encounters and minimize fuel usage. Again, as with the mission overall, the encounter geometries have not yet been finalized, and so the navigation system must be flexible enough to deal with a variety of geometries. Table (list of NAV activities, time frame and requirements) gives a general indication of the types of services and their constraints which navigators must provide the mission.

Table 1: New Millennium DS-1 Navigation Attributes and Requirements

Time of Operation	Operation	Accuracy
Launch + 5d	Asteroid astrometry and OD	1 micro-radian or 100-200km
brunch + 30d	Injection Trim OD and SEP Control	0.1-05 meters/sec
Asteroid Enc.-5d	Target Acquisition	12 th Magnitude
Asteroid Enc.-3d to Enc - Od	SEP and/or Chem-ical control	Delivery to 10km, Control to 1 k!])
Comet Enc.-20d	Acquisition, OD of inner Coma	50 micro radians or 1000 km
Comet Enc.-5d	Acquisition, OD of outer nucleus	50 micro radians or '250 km
Comet Enc.-1d	Acquisition, OD of nucleus	10 micro radians or 10 km

CONCEPTUAL BASIS OF THE AUTONOMOUS NAVIGATION SYSTEM:

The system being built for New Millennium DS 1 is a complete navigation and control system. In this case "navigation" refers to those processes necessary to determine the spacecraft position, or orbit and to correct excursions from a desired course, based on a determination of the spacecraft position. There are three reasonably distinct regimes in which the Navigator will have to operate: departure, cruise and encounter, and the nature of the orbit determination (OD) and control problems differs somewhat in each.

Departure Phase

Potentially, if post-launch requirements were sufficiently demanding, the navigator could take images of the Moon and Earth on departure and use these for trajectory determination very much as the *Voyagers* did on approach to Jupiter, Saturn, Uranus and Neptune. However, the demands on the departure phase for *DS-1* are not severe, and so this process will not be necessary. In addition, as *DS-1 irr* the first flight of a deep space autonomous navigator, some early earth-based navigation will be performed as a validation, further obviating the need for high-precision earth-moon target optical data

Cruise Phase

The cruise phase images used by the OPNAV system are those of asteroids and stars. Though typically many tens of millions of kilometers distant from the spacecraft, these images taken regularly and frequently provide a very good means of determining the spacecraft state (position, velocity and associated force models). Each individual picture represents a datum. Based on the ephemerides of the navigation target (beacon) asteroids, predicts of the star-relative positions of the asteroids are computed, and differences between these and the observed positions are the "residuals." Partial derivatives of the object positions with respect to spacecraft position, velocity and possibly perturbing forces are computed. Using the partials and residuals, estimates of these parameters are computed in a linear least squares filter .[6] Using techniques derived from the *Galileo* it, iage processing system, long exposure images of asteroids can give astrometry good to about a micro radian or 50 to 100km for typical beacon asteroid ranges

Encounter Phase

The encounter phase of the mission can, and likely will be performed with two types of optical image, those of the destination object (target) with stars and images of the target without stars. Depending on the sensitivity and dynamic range of the camera, it may not always be possible to image the approach target simultaneously with a star; the exposure required would be too long, inducing unacceptable smear, or causing the target inrage to overexpose, Images of nearby objects saris-stars, such as of the target, do have some value however. For *DS-1*, as is typical of most spacecraft with remote sensing instruments, the bus orientation, is controlled to a reasonable accuracy by the attitude control system (ACS). That accuracy for *DS* 1 is about a milli-radian, or about 100 pixels, This control accuracy is a factor of a thousand worse than the OPNAV system can reconstruct the pointing if stars are present. Fortunately, the ACS with its precision star scanner/tracker has *knowledge* of bus pointing good to about 100 micro radians, or 10 pixels, At one day from encounter (assuming a 10km/sec closing velocity) this implies a data accuracy of 100km, vs. lkm for a pointing analysis using images with stars. However at 30 minutes from closest approach, pointing provided by the star tracker would produce a 2km measurement. Though achieved too late to control the spacecraft trajectory, this measurement accuracy is sufficient to control spacecraft pointing. Both types of encounter measurements are entered into the state estimation filter in exactly the same manner as the cruise data.

Trajectory Control

Throughout the mission it is necessary to perform some measure of control to the spacecraft position. For a conventional "chemical" [usually hydrazine) powered mission this is accomplished by periodically performing very short maneuvers (on the order of a few minutes) with relatively high thrust engines (cm the order of 1 Newton for *DS-1*). *These* corrections represent small perturbations to an otherwise ballistic trajectory, the great majority of the crier gy of the interplanetary orbit having been imparted by a large burn of a chemical engine, which is discarded. These injection burns are typically severs] km/see in size. The advantage of "low t),r-List" missions is that they may be launched into interplanetary orbit with very low earth-relative energy on a small launch vehicle, and slowly accrue that energy hy continual thrusting. This is made possible by the extremely high efficiency of the ion drive engines.

For the NSTAR Solar Electric Propulsion system being flown on *DS-1*, the thrust of the engines is approximately 40 milli Newtons, but because of the engine efficiency, the spacecraft carries the delta-v capability of about 3 km/sec with only about 40 kilograms of propellant (xenon). A very different type of mission design is necessary for a low thrust mission[7], and a very different form of "control" is called for as well. Since the main ion engines are thrusting for long periods of time, this provides a means of correcting errors in the trajectory. The control algorithm to be used for *DS-1* takes advantage of this "continuous control". The thrust arc is broken up into periods of constant thrust magnitude and direction interspersed with periods of coasting. The thrust direction, magnitude and time parameters are established well before launch, and constitute the mission design. The navigator will have an opportunity to update these parameters on a regular basis. At the time of each update, the navigator will perform an orbit estimate, and compute the changes necessary to correct any orbit dispersions by making small corrections to the direction and time of each thrust period.

The method used to compute these parameters is very similar to that used to compute the chemical maneuver parameters. Schematically the process is as follows: the current estimated spacecraft state propagated to the target and differenced with the desired aim point is the targeting error. At the specific time of a maneuver or thrust arc, a matrix of perturbation partials, (targeting changes as a function of maneuver parameters) can be computed. The inverse of this matrix times the targeting errors represents a linear estimate of maneuver parameters. Often, when the maneuvers are relatively small, and the encounter involves little or no gravitational interaction, as is the case with DS-1, such a linear estimate is adequate

THE IMAGING SYSTEMS AND IMAGE ANALYSIS

Camera Requirements

Critical to any OPNAV system are the specifications of the camera to be used for the data taking. The requirements for navigation imaging are not necessarily straight-forward to state. There is a reasonably complex interplay between spacecraft and camera requirements. Table 2 gives a summary of OPNAV requirements on an imaging system for an interplanetary optical-only navigation system. One of the most obvious trades is aperture size (effectively the light gathering area) vs. spacecraft bus stability. For a number of reasons (not having to do with navigation) the spacecraft will suffer relatively large ambient motions, up to 100 micro radians/see. For the currently considered camera, that represents 10 pixels/sec smear rate.

Another trade-space is the field of view. Though the narrower the field, the greater the potential accuracy of the OPNAV data, a narrower field also increases the effects of smear, and makes planning and acquisition of stars more difficult. The issue of sensitivity is also tightly correlated to ambient motions, and to aperture. The ability of the cruise imaging mode to take long exposures makes the navigation system somewhat less dependent on absolute system sensitivity. However some high-accuracy encounter modes of operation are dependent on short unsmeared exposures, and thus the system sensitivity has some influence on overall navigation capability, The issues of sensitivity and dynamic range are also coupled. All other factors equal, and assuming a low-noise system, a dim star may be detected at a lower signal level in a high dynamic range system than with lower dynamic range system. This is important, because a longer exposure could overexpose the target object with a resultant reduction in centerfinding accuracy or destruction of the frame due to camera/electronic effects.

Table 2: OPNAV Requirements for Imaging Instrument
1) 10 cm Aperture
2) 12 bit Digitization
3) Programmable Gain States
4) 0.6 to 2.0 Degree Field of View
5) 0,1 Pixel Centerfinding capability --- Focused Ima e
6) 80000 Minimum Full Well, with 50 e- Noise
7) Image 9th Magnitude Star in Best S/C Control Mode A

Image Processing

As mentioned earlier, for the cruise portion of the mission, the principal means of image processing will be the SFM technique developed for the *Galileo* asteroid encounters. This method overcomes the smearing the unresolved (star-like) images of stars and distant asteroids. The pattern of smearing is not predictable and therefore unmodelable. The process performs a multiple cross correlation between all of the navigation objects in order to obtain their position. The key concept of the SFM technique is that all object images suffer the same distortion due to camera motion, Even though the object images (both stars and asteroid(s)) appear in different portions of the frame, the pattern exhibited is nearly identical. Each object may be used as a pattern for locating each other object. Given a normalized pattern, called a "filter", that is composed of image elements in a matrix $m \times n$ in size denoted as F, and a sample area S $M \times N$ in size of which subset regions of $m \times n$ dimensions are extracted, then a function c_{ij} can be maximized:

$$c_{ij} = F \otimes S_{ij} = \sum_{k=1}^{m} \sum_{l=1}^{n} F^{kl} \cdot S_{ij}^{kl}$$

The maximum of c_{ij} represents the position of best match between F and the sample region The details of these algorithms are discussed elsewhere[4]

For encounter operations, the nature of the image processing becomes quite different. Because the target object eventually becomes resolved, extended exposures will become impractical because it would be essentially impossible to find the center of the image of an extended object which resulted from extensive smearing. These short exposure, extended image "science-like" OPNAV frames will be analyzed either using centroiding algorithms, or using modeling and limb fitting. These techniques are discussed in depth elsewhere as well[8,9].

THE AUTONOMOUS OPNAV SYSTEM DESIGN:

Navigation System Architecture

Fig. 2 shows the overall structure of the DS-1 flight system software. All of the elements of the flight software exist as separately launchable processes. The processes communicate through an asynchronous message handling system, As shown in the diagram, the NAV system is comprised of 3 elements: 1) a navigation Preprocessor, 2) a navigation Ephemeris server, and 3) the main Navigator.

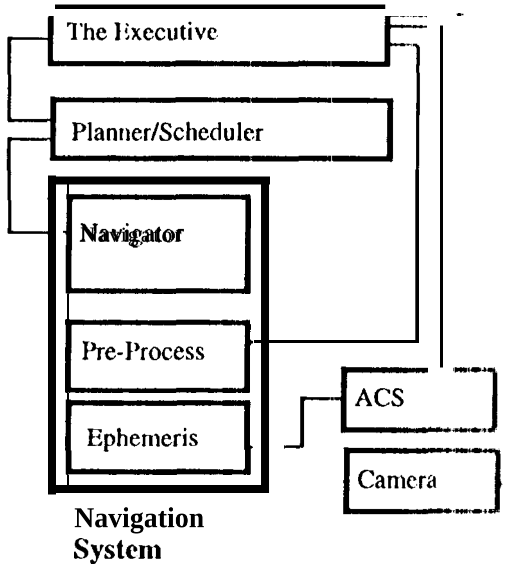

Fig 2: Autonomous Flight Software Architecture

The Pre-processor's principal task is to identify, via computed predictions, the navigation object s in a newly taken frame. Since the predictions of position can only be as good as the pointing control (about 500 micro radians) the preprocessor must search for the objects of interest. This searching is performed in a method derived from the *Galileo* onboard OPNAV data editor. A pattern of object positions is provided (the position predicts) and the mutual difference-vectors of position represent a template pattern. The frame is scanned for regions of brightness candidates -- which might be images or noise. The set of candidate positions is mutually difference, representing sets of candidate patterns. These are searched and compared with the template. The candidate pattern which compares most favorably with the template is chosen as the anchor for a preliminary determination of positions. A local centroiding process improves this determination. Finally, the local regions around the registered positions are extracted and stored, allowing the spacecraft mass storage manager to release the original frame. The initial center finding increases the efficiency of the subsequent cross correlation process.

The ephemeris server is a means for the OPNAV system to provide the rest of the spacecraft, principally the ACS (Attitude Control System) with ephemeris information. As part of the Nav system data base are ephemeridies of all of the major solar system bodies, the target asteroid and comet, and perhaps as many as 250 additional "beacon" asteroids to be used as navigation targets only. Additionally, Nav carries a star catalog for portions of the sky inclusive down to 13th magnitude, All ephemeridies are determined on the ground. The planetary ephemeridies, though very high accuracy, are not *per se* used for navigation, but to target specific events, *e.g.* pointing the high gain antenna to Earth. For *DS-1*, planets will not be used as targets, their distance and size make them less beneficial than close small asteroids. However, the asteroid ephemeridies are not nearly as accurate, with positional errors ranging from * few tens of kilometers for the largest asteroids to several hundred for the smallest. Varying accuracy of the beacon asteroids can be dealt with in a number of ways. A short earth-based observations campaign to improve the asteroid ephemerides before launch is the preferred means. Alternatively, many different beacons can be used in an effort to dilute or average out the large errors of specific beacons. Another option would allow for the estimation onboard of the beacon asteroid ephemeris, however this is not the preferred method as it significantly complicates the structure of the navigator.

The Navigator

The main computational element of the onboard system is the "Navigator." It is the program responsible for planning the picture schedule, high precision image analysis, orbit determination anti trajectory control; and it performs these functions via interactions with the onboard autonomous spacecraft planner and executive, known as the "Remote Agent." Fig. 3 shows a wry simplified functional diagram of the Navigator, The structure of the Navigator is basically an event loop, The Navigator is always running, but waiting for messages from the Planner or Executive. The planning cycle and the major operations of the Navigator and the stimulus for their invocation will be discussed below in detail,

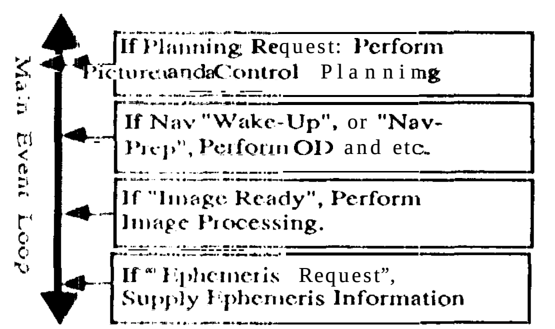

Fig. 3: The Main Navigation Event Loop

1. The Planning Cycle

For *DS-1*, onboard operations will be divided up into planning cycles, The length of these cycles will vary during different phases of the mission, but will probably be about a week long during cruise, anti be from an hour to perhaps a few minutes long during the encounter. Fig 4 shows schematically a planning cycle emphasizing navigation events, with a key given in Table 3. The Executive executes plans generated by the Planner. When the executive nears the end of a plan, it invokes the Planner to design the next plan. The Planner asks all pertinent onboard elements what their planning requests are, and applies certain constraints and requirements on their plans In the case of navigation, the planner asks the navigator to plan its pictures within s sequence of observation windows. These windows are chosen to avoid communication events and other activities. The navigator responds with a list of targets for each wit, dow, and also with a series of specifications on the SEP engines if planning is for a thrusting period. Additionally, the navigator may request a specific maneuver, either with the chemical or SEP system if planning is for an approach phase.

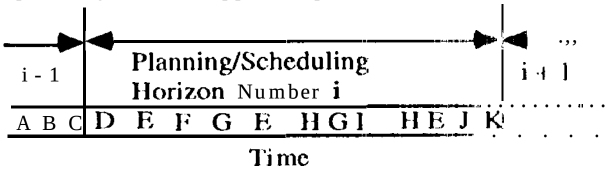

Fig 4: Diagrammatic Representation of a Planning Cycle (See Table 3 for Legend)

Table 3: Planning Cycle Event Key
A) Planner requests NAV Plan for Horizon i
B) End of execution of Horizon i-1
C) NAV provides picture and maneuver request
D) Start of horizon execution
E) OPNAV observation window, several frames
F) Request for ephemeris data, NAV replies
G) Opportunity for the Navigator computation
H) Maneuver (TCM) or SEP thrust status change
I) Plan Request and NAV response for i + 1
J) End of Planning Horizon i
K) Start of execution of horizon i + 1

2. Picture Planning

Upon receipt of a request for planning, the Picture Planning module produces a set of picture requests to be submitted to the planner. There are several levels of autonomy that the Picture Planner may use. At a minimum level 1, a list of beacon asteroids as a function of time may be provided to the Navigator at launch. These beacons are chosen to maximize the information content in the frames. Several factors influence the information content: Proximity to the spacecraft (the nearer, the more information); brightness (the brighter the image the more accurate the astrometry), brightness in turn is also influenced by the size and albedo of the asteroid, and also by the phase angle (sun asteroid spacecraft angle); sufficient quantity and quality of Stars in the frame; and accuracy of the beacon ephemeris. Higher levels of autonomy can be invoked by having the onboard picture planner find optimal sets of beacon asteroids using the aforementioned criteria rather than doing this on the ground prior to launch. Given a selection by these criteria try whatever means, the planning process will have clustered the best beacons together in several "lines-of-sight" which provide the greatest combined determination of a local instantaneous state. A minimum of two such lines-of-sight are necessary to obtain such a state. Typically in each OPNAV opportunity four lines of sight will be obtained with several images taken of each, Additionally, the navigator will tell the planner the span of time over which each particular line-of-sight is usable. This is principally a function of the spacecraft- beacon- asteroid velocity vector. For typical cruses OPNAV pictures this period of time will be several hours. As discussed earlier the cruise images will be long exposures, taking advantage of the spacecraft ambient motions. As such, usually there will be several stars, albeit smeared, in the frame. Fig 5 is an experimental ground simulation of such an image taken from JPL's Table Mountain Observatory.

For encounter operations, planning is somewhat more difficult. As discussed above, for images containing an extended image of the target and a star, the exposure time is liable to be short, implying at most one or two stars will be visible. Also being near the target implies that the relative motion of target and spacecraft will be large. The *net* effect of these considerations is that the number of opportunities will be small and that they will have very short windows of opportunity, possibly only a few minutes or even seconds. Also the primary emphasis for the Picture Planner during encounter will be to locate any star of sufficient brightness in a frame with the target body, in stark contrast to the cruise planning where the number of stars in each frame could be maxirnized.in either encounter or cruise mode, the navigator replies to a planning request with statement containing a series of windows in which particular lines-of-sight (containing navigation targets) are viable. Additionally, the navigator sends the requested parameters associated with the pictures to be shuttered in these windows, such as exposure time, gain, and filter.

3. Maneuver Planning

As discussed briefly above, there are two different conditions under which the maneuver planner needs to operate. During continuous SEP thrusting periods the Maneuver Planner must make periodic use of the currently best-estimated orbit to update the thrusting profile. On approach to the target, discrete Trajectory Correction Maneuvers ('["CM'S) must be performed to correct the arrival point and time toward the desired aim point. The thrusting is performed in cycles. Cycles will ranges from as long as 14 days to perhaps a half day. The cycle is characterized by a fixed start time, and a narrowly variable stop time. interspersed through the cycle are gaps of SEP thrusting. These are induced by the need to take OPNAVs, communicate with the ground, or by *other* events requiring a bus pointing away from the SEP orientation, or otherwise turning SEP ofi.

Because of the autonomous nature of the flight operations, these "non-SEP" events can only be qualitatively characterized. The mission thrust profile is designed assuming only general knowledge about the specificity of such events, and that as a result only a limited amount of time IS allocated over the thrusting arc fOr actual OperatiOn of the SEP thrusters. For *1) S-1* it is currently assumed that 80% of the time during a thrust arc is available. This 20% "non-SEP" allocation includes 6 to 10% reserved in a block at the end of the thrusting arc. This is reserved partly as "margin" in the sense that anomalous non-SEP events may occur. At least one-fourth of this dedicated non-SEP block is reserved for Navigation control.

As mentioned earlier, computation of the control parameters happens well before the actual control begins. In the case of cruise SEP control, the time the control will begin (i.e. the moment at which a change in status of the SEP engines will take) place is known to an accuracy of a few minutes. However, since the engine thrust is low and the control is in effect a change in the thrust direction and/or duration of only a. few percent, and that control is taking place in cruise (as opposed to encounter) the precise starting time is unimportant. The maneuver parameters are given by

$$\begin{bmatrix} \Delta ra \\ \Delta dec \\ \Delta t \end{bmatrix} = \hat{K}^{-1} \cdot \begin{bmatrix} \delta b \cdot r \\ \delta b \cdot t \\ \delta t_{flight} \end{bmatrix}$$

where Δra and Δdec are changes in the thrust direction and Δt is the change in duration, $\delta b \cdot r$, $\delta b \cdot t$ and δt_{flight} are the errors at the desired target time. K is the partials matrix of changes in state at the encounter time as a function of the 3 control variables. In general, K must be numerically computed by integration of the spacecraft position from the reference state to encounter using the nominally designed thrust profile forecast into the future. Force models germane to *DS-1* have been added, including Solar Pressure, n-body solar-system perturbations, and a model for the thrust of the ion engines. This process is generally iterated several times, starting with "O" initial values for the maneuver parameters and updating the next iteration with the results of the last.

For *DS-1* it is probably the case that this linear parameter estimation with iterations will be adequate. For other missions that may involve planetary rendezvous or one or more gravitationally significant encounters, initial search procedures will need to be invoked to treat severe non-linearities of the encounter conditions. Computing better initial conditions than "O" is one approach to improving the stability of the iterations. An initial guess using a Lambert targeting algorithm has been implemented for non-SEP portions of the trajectory, such as the approach to encounter.

The process described here is virtually the same for discrete TCM's as for the SEP thrust corrections. Additionally, discrete TCM's may be accomplished using SEP as well, again using the same computational approach. The difficulty is that the spacecraft bus, and therefore the SEP engine cannot be pointed to all regions of the sky because various instruments and devices with s , n and/or illumination constraints preclude this. However, the direction angles of a burn required to remove trajectory errors that are statistically induced may point in any region of the sky. This is not an uncommon situation with spacecraft, although *DS-1* may be more restricted than most in this regard. The common treatment of such a problem, which applies to both types of thrusting (though not to the same degree), is to "vectorize" the TCM. Vectorization is the simple decomposition of a forbidden thrust angle and magnitude into two allowed ones. Unless a very large portion of a contiguous hemisphere of the sky is forbidden, this worka quite well for chemical TCMs using the analysis above and applying a simple geometric decomposition, The actual decomposition of the TCM is likely to be done, not by the Navigator, but by the ACS system. This is possible due to the high thrust short duration of chemical maneuvers. Since the burns are short, on the order of a few minutes, they are dynamically effectively simultaneous, and so the two components, with a small error, may be separated into two disjoint parts. This process will not work for SEP control. The burn periods are long, and might in fact, for an approach correction, occupy a significant portion of the remaining time to encounter. The dynamics of the problem of vectorization become difficult and nonlinear, and make otherwise simple interactions with the ACS, Executive and Planner/Scheduler much more complicated. As a result, the Navigator will choose to perform SEP powered TCM's where possible, and will requite the use of chemical TCM's when vectorization is necessary.

After all computations are complete, the Maneuver Planner will issue a command to the planner, containing the direction, execution time and duration of the requested chemical TCM. Or, a commrrnd will be issued, making a request to change the SEP status (e.g. a change of thrust direction), or to perform a discrete SEP TCM. For both types of SEP control, the duration parameter is handled in a very different manner then for chemical TCM's. Rather than the ACS automatically timing the opening and shutting of valves, the autonomous Executive, based on the Navigator-supplied parameters, will have to command the initialization of the SEP thrusting, and then begin monitoring the accumulated thrust time. For a small TCM, this is straightforward, but for a cruise control event, the thrusting may be interspersed with non-thrusting periods, making the tracking of the accumulated time a required activity of a high level function like the Executive. This fact, that the clock-time length of a maneuver cannot be predicted, is the prime reason for the gaps of time at the end of each thrusting cycle. As the executive places more or fewer non-SEP events into the arc, the clock-duration of the burn will extend into or retreat from the nominal end-of-thrust boundary.

4. Orbit Determination

One very important aspect of the orbit determination process as it needs be performed autonomously for *DS-1* is a ramification of the nature of the optical data compared to Earth-based radio-metric data. Doppler data makes a direct measurement of line-of- sight velocity; ranging data makes a direct measurement of line-of-sight distance. Although these two measurements are very precise in general, the other four dimensions of the state must be obtained by inference from second order signatures on the signal (such as due to earth diurnal and orbital motion), and/or integrated over time from a previously determined state[10] As such, radio data is very sensitive to any source which might effect the signal. Necessarily, very precise models of all possible dynamic perturbations to the spacecraft and earth must be maintained, these include very accurate models of the performance of the SEP engines (something which might be very difficult to obtain), and currently updated models of the earth's polar excursions, tables of which need to be updated weekly at a minimum. Additionally, current estimates of atmospheric signal delay calibrations often need to be maintained. These factors combined would imply that an autonomous radio navigation system would be difficult to build, besides the obvious disadvantage of requiring a (probably) coherent ground track.

Optical data has none of the problems listed above. Images of distant asteroids or of the target give a direct measurement of two components of the position. With a turn of a few tens of degrees and the image of a second target, the third component is obtained. Velocity is not obtained **directly,** but neither must it be inferred from second-order effects; **simple differencing** of states in time **gives an** explicit velocity measurement. The calibrations of the optical system are much simpler, and most likely need be done only once with a few images of star fields. Although the **potential** power of radio data is huge (as good as 0.1 micro radian earth-relative, giving 15km at 1 AU from Earth) it is this very power, requiring the extremely accurate modeling alluded to above, which hinders it's use in onboard autonomy. In interplanetary cruise, the OPNAV system may be capable of state determinations of little better than **100km;** but this is more than adequate. Furthermore, this much looser **determination** of state allows a much relaxed modeling standard; no aspect of the orbit determination is dependent upon modeling any component of the spacecraft motion to a few meters or a fraction of a **mm/sec** as is the case with radio data. Finally, the most important advantage of optical data is that it gives target relative information. Unless the ephemeris of the target object is perfectly known (effectively true only for the inner planets) an OPNAV system will have to exist in order to provide final approach guidance.

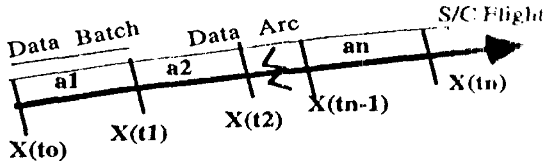

Fig 6: Schematic of Data Arc Structure

The above discussion implies that the structure of an orbit determination filter for optical **data** may use strategies other than what might **be optimal** for filtering. radio data A **final** but additional difference is data frequency: optical data arcs are sparse, with a few tens of observations per week; radio data arcs may acquire many thousands of measurements per day. Fig 6 shows the subdivision of the data arc into batches over which an estimate parameter set is **constant.** $\mathbf{X}(t_0)$ is the spacecraft state at the start of the data arc, $\mathbf{X}(t_1)$ at the start of the second batch, etc. $\mathbf{a}_n$ is a vector of acceleration errors, representing errors in the modeled **SEP** thrust, or possibly errors in other dynamic models such as solar **pressure** For any observation made at **time** t within batch one, the filter must **integrate** the state X(t), and the state transition **matrix.** The later has two components, for the state itself $\partial\mathbf{X}(t)/\partial\mathbf{X}(t_0)$ and for the dynamic force parameters $\partial\mathbf{X}(t)/\partial\mathbf{X}(\mathbf{a}_1, S)$ where S is a vector of other force models, including solar pressure. For this **observation** at time t, and for subsequent observations a **measurement** matrix **A** can be formed:

$$A = \begin{bmatrix} \partial O_1 / \partial q \\ \partial O_2 / \partial q \\ \vdots \\ \partial O_n / \partial q \end{bmatrix} \quad ;where\ \frac{\partial O_{2\times1}}{\partial q} = \frac{\partial O_{2\times1}}{\partial X} \cdot \frac{\partial X}{\partial q}$$

On is the observation vector for **observation** n, and is a 2x1 vector, (pixel **and** line). The formulation of $\partial\mathbf{O}/\partial\mathbf{X}$ is documented elsewhere[2,3]. q is a vector of estimable parameters, and for batch 1, q [$\mathbf{X}(t_0)$, $\mathbf{a}_1$, **S**]. A is combined into a covariance matrix referenced to to, Γ_{t_0}, via a **UD** factorized orthogonalization procedure [6] an example of which is known as the Householder transformation. To process data in batch 2, an additional parameter must be added to the estimate vector, namely a2 the acceleration errors for batch 2. Thus for batch 2, q2 - [$\mathbf{X}(t_0)$, $\mathbf{a}_1$, $\mathbf{a}_2$, **S**] and the filter will integrate X from t_1 to t2, as well as $\partial\mathbf{X}(t)/\partial\mathbf{X}(t_1)$ and $\partial\mathbf{X}(t)/\partial\mathbf{X}(\mathbf{a}_2, \mathbf{S})$. The state **partials** for a time t in batch ? relative to the solve-for epoch t_0 and those with respect to $\mathbf{a}_1$ are given by:

$$\frac{\partial X(t)}{\partial X(t_0)} = \frac{\partial X(t)}{\partial X(t_1)} \cdot \frac{\partial X(t_1)}{\partial X(t_0)}, and$$

$$\frac{\partial X(t)}{\partial a_1} = \frac{\partial X(t_1)}{\partial a_1} \cdot \frac{\partial X(t)}{\partial X(t_1)}.$$

And in general, for batch n, where $\mathbf{q}_n$ - [$\mathbf{X}(t_0)$, $\mathbf{a}_1$, $\mathbf{a}_2$... $\mathbf{a}_m$, .. $\mathbf{a}_n$, **S**]:

$$\frac{\partial X(t)}{\partial X(t_0)} = \frac{\partial X(t)}{\partial X(t_{n-1})} \cdot \frac{\partial X(t_{n-1})}{\partial X(t_0)}, and$$

$$\frac{\partial X(t)}{\partial a_m} = \frac{\partial X(t_{n-1})}{\partial a_m} \frac{\partial X(t)}{\partial X(t_{n-1})} \text{“}$$

where $\mathbf{a}_m$ **is** an arbitrary **thrust error** vector from an earlier batch. When all of the data from all of the batches is combined into **A** and Γ_{t_0}, an estimate of the parameters can be made:

$$\begin{bmatrix} X_{t_0} \\ \bar{a} \\ S \end{bmatrix} = \Gamma_{t_0} A' W A y,$$

$$\Delta y_{1\times2N} = O_{2\times N} - C_{2\times N}$$

where Ay is the residual vector formed as the difference between the observation vector O and the computed predicted value **C**. **W** is the observation weighting matrix. N is the total number of frames taken, and 2N is the number of data (pixel and line for each). Iterations are performed on this solution, repeating the solution one or more times with the improved integrated ephemeris and force models from the previous solution. When the solution is converged, the elements of **a** are not equally well determined; $\mathbf{a}_1$ is the best determined, as all of the data in the data arc influence a measurement of $\mathbf{a}_1$, whereas **an is** the poorest, as only the last batch has an influence on its solution. When it becomes necessary to update the epoch of the solution, a reasonable compromise must be made as to the accuracy of the **a vector. A** reasonable choice is to update the epoch state to a point half-way through the current data arc, effectively requiring reprocessing of half of the dat a, but with an improved integrated spacecraft state based on data beyond the new epoch-state. This is in effect one final iteration of the solution, as well as a single pass smoothing. To get the covariance to start the next solution cycle the covariance at t_0 must be mapped forward in time:

$$\Gamma_{t_{n/2}} = D\Phi_{t_0}^{t_{n/2}}\Gamma_{t_0}\Phi_{t_0}^{t_{n/2}\prime}$$

where $\Phi(t_0,t_{n/2})$ is the state transition matrix from t_0 to the midpoint of the data arc. D is a de weighting matrix to allow for errors accrued due to unmodeled perturbations.

The process of analyzing the accumulated picture data, and performing an orbit solution (Orbit Determination) is not strongly under the control of the Executive. Based on timing parameters derived from ground based analyses, the Navigator will periodically decide to perform this function. It is inefficient to perform this process after every acquisition of data, computationally expensive to wait until the current state is needed for planning, and unsafe to do so in view of the fact that some failure onboard might be inducing errors in the data or elsewhere which would be undetectable until after the data is processed or the state determined. However, the Executive does need to balance competing uses of resources, in particular, compute resources. Since both the Sequencer/Planner and the Navigator are heavily compute-intensive processes, the executive will notify the Navigator of an impending planning event. This may induce the Navigator to perform an Orbit Determination process, if there is accumulated unprocessed data, as well as other associated functions.

5. Failure Detection

The issue of failure detection and avoidance in an onboard autonomous system is very important, and applies to the Navigator as well. The principal means that the navigator has to detect internal or external system errors is by evaluating the quality and quantity of data it receives. There are several layers of checks or "gates" through which the data passes before it finally may influence an orbit solution, The first gate is the Preprocessor. As discussed earlier, the Preprocessor will search in areas of the frame where objects are predicted to be, and obtain initial rough positions of them. If a sufficient number of objects aren't found, or their brightness is inadequate, the Preprocessor will flag a problem, or even flag the picture as unprocessable. Such an occurrence could indicate problems with the camera, the attitude control system, or *erroneous or* damaged navigation data, such as the beacon-asteroid ephemerides. The second gate is the SFM Image Processor. If the initial determined positions are too far from predictions, the SFM processor will fail, indicating misidentification, or anomalous orbital errors. The third gate is to use the precision locations from the SFM processor to determine an instantaneous state through triangulation with another line-of-sight observation. The instantaneous states when compared with the current best estimated and propagated state provide another check. Excessive differences indicate a bad "blunder" point or other problems. Data passing the first three gates enters the filtering process. Pre and post-fit residuals provide yet another means of removing bad data anti/c~[indicating chronic system problems. In all cases discussed here, individual bad data points are deleted, but accumulations of bad data will indicate larger problems which will likely be referred to earth for diagnosis. In at least one instance however there is action other than "Call Home" (for help) for the Navigator to request of the Executive. This is the case where the Planner/ Sequencer has simply not scheduled enough of the requested OPNAV pictures to achieve adequate performance; this would have happened if events of nominal priority have superseded navigation frames. If this occurs, the Navigator will increase the priority which it assigns to its picture requests in presenting them to the Planner. If as a result sufficient images are still not obtained, the Navigator will continue to increase the planned priorities to the maximum allowed by system design parameters. At this point, if still insufficient images are being obtained, the Navigator will request *a* "Call Home"!

PRELIMINARY N1MULATION RESULTS

A preliminary version of the autonomous navigation system has been built and tinted as a prototype of the version to be flown on the DS-1 mission. This operational version currently assumes a ballistic (non SEP) mission; the version to incorporate navigation of a SEP mission is still under *development*. *The system* has been tested on several mission types including an early candidate DS-1 mission which used a ballistic trajectory to fly by the asteroid Melpomene. The results of this simulation will be given here. The purpose of the simulation is to incorporate realistic error sources (both random and systematic) into the "truth" trajectory to see how well the navigation system performs.

The scenario for the Melpomene mission starta with a launch on February, 1998 into a direct interplanetary **transfer,** with the flyby occurring approximately 11 months later. During cruise, there are four TCMs which take place at Encounter (E) 293 days, E - **203** days, E - 53 days, and E - 3 days. All the TCMs are statistical in nature, that is, they are nominally zero and are used only to remove the deviations of the true flight path from the nominal. The largest of these TCMS will TCM-1 which cleans up launch injection errors. Typically, this maneuver uses 40 . 60 m/s of delta-v. The second, third and fourth TCMs arc much smaller (on the order of m/s to cm/s) and remove the effects of random rind systematic perturbations which affect the trajectory. **The purpose of the navigation** *system* **is** *to determine* **the orbit based** on the beacon asteroid sightings and then compute the required maneuver delta -v at tile appropriate times to take the spacecraft back to its targeted aim point for the flyby. The aim point is given in terms of the B-plane -- an imaginary plane centered on the target body and perpendicular to the incoming asymptote of the trajectory. The orthogonal coordinate system axes of the B-plane are B*R and B•T in the plane itself, and time-of-flight (TOF) which perpendicular to the plane and along the asymptote.

The results of the Melpomene simulation are ahown in Table 4, which gives the 1- sigma statistics of the OD solution mapped to the B-plane prior to performing each of the TCMs. The accuracy of the TCM in delivering the spacecraft to the target depends on the accuracy of the OD solution and the execution errors in the TCM. Execution errors are roughly proportional to the size of the maneuver so in general, the better the OD, the more accurate the delivery. The final column in the table shows the actual error between the estimated B-plane value and the 'truth' value for a single realization of the simulation. The errors are for the most part, within the l-sigma uncertainties computed by the filter except for the solution for TCM-3, which had errors in the 2-3 sigma range. Although a complete Monte-Carlo simulation was *not* performed, all runs pm-formed so far have exhibited similar behavior. The final delivery to the target at E -3 days is on the order of tens of km, which is comparable to what a ground-based radio system can do. Beyond this stage, centroiding techniques for extended bodies can be used to further refine the knowledge of the flyby point to sub-kilometer levels[8].

Table 4 DS-1 Melpomene Simulation		
Time to Encounter	Mapped OD uncertainties (sigma B• R x B•T x TOF) (km, km, s)	Actual errors (B•T x B•R x TOF) (km, km, s)
E -293 days	24,562 x 6396 x 4743	20,7?/(1 x 4193 x 4132
E - 203 days	2535 x 1411 x 498	154 x 39 x 63
E - 53 days	163 x 191 x 36	314 x 275 x 118
E - 3 days	18 x 19 x 26	11 x 1 x 23

Another entirely different aspect of the prototype Autonomous OPNAV System has been tested. When the scope of the other onboard systems became known, but well before any testable prototypes were available, it was decided that, at a minimum, an interface test of the Navigator working with an autonomous Sequencer was necessary. Such a system was fortunately nearly available, components of which had been developed for sequencing and planning for *Voyager, Galileo* and *Cassini*[11]. In fact, development of the parallel simulation in large measure guided the system design of the Navigator. This autonomous Sequencer takes a very pragmatic approach, toward onboard autonomy. Rather than try to achieve optimum control and efficiency at all levels of spacecraft activity, assumed bounds of time and resource are allocated to all activities, Then, in a process very similar to ground-based sequence planning, blocks of activities can be scheduled, and resource conflicts readily resolved. Though sub-optimum, such a planner is very fast, and amenable to ground input and control. When combined with this planner, the Navigator was able to make requests of images, and have them planned, receive and process the results, and schedule maneuvers. *In* the meanwhile the Sequencer was able to schedule science frames using the latest navigation data, and in most cases achieve a near optimum level of science-imaging return.

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